

NONLINEAR ROBUST CONTROL OF FUNCTIONAL ELECTRICAL
STIMULATION SYSTEM FOR PARAPLEGIA

MOHAMMED AHMED

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Dedicated to my grandparents



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ABSTRACT

The study was directed towards enhancing Functional Electrical Stimulation (FES) for sit-to-stand movement restoration in paraplegia subjects. The scarcity of FES assistive devices was due to the inability of the developed equipment to attain clinical acceptance. Applications of control systems have shown fruitful results. And based on the literature, further improvements in model, trajectory and control systems are needed. Model with a higher level of accuracy and continuous as well as bump-free trajectories are essential ingredients for better control systems. The control systems can be enhanced by giving considering to changes in mass of the subject, disturbance rejection and stability. Hence, the comprehensive control scheme is necessary for this application as well as a better model and trajectory. In modelling an additional joint has been considered to improve the accuracy. In trajectory planning, the six-order polynomial has been used to refine the desired trajectory. The comprehensive control systems have been designed with consideration of robustness, disturbance rejection, and stability. Three nonlinear control approaches have been investigated; the Sliding Mode Control (SMC), Feedback Linearisation Control (FLC), and Back-Stepping Control (BSC). Results reveal improvements in the accuracy of the kinematic model by 24%, and the dynamic model by 47%. The trajectory planning parameters are continuous, and not susceptible to jerks or spikes. Execution time enhanced by 11%, the upper and lower terminal velocities improved by 16.9% and 20.9% respectively. The system response without disturbance shows good results with the SMC, FLC, and BSC. Revelations by robustness examination also maintain remarkable enhancements in the parameters with both 53% and 126% mass. The results for disturbance rejection examinations with fatigue, spasm, tremor, and combined disturbance effects showed sustenance of refinement in the response parameters. Therefore, indicating improvements despite the changes to the system. The BSC showed the best performance, followed by the FLC, and the SMC. Hence, the BSC is recommended for such systems.

ABSTRAK

Kajian ini bertujuan meningkatkan keupayaan Stimulasi Elektrik Fungsional (FES) untuk memulihkan pergerakan duduk dan berdiri untuk subjek paraplegia. Kekurangan alat bantuan FES adalah kerana ketidakupayaan pembangunan peralatan untuk memenuhi keperluan klinikal semasa. Aplikasi sistem kawalan telah menunjukkan hasil yang memuaskan. Berdasarkan kajian terdahulu model, trajektori dan sistem kawalan perlu penambahbaikan. Model dengan tahap ketepatan tinggi dan trajektori yang berterusan seperti bebas-lantunan merupakan aspek penting untuk sistem kawalan yang lebih baik. Sistem kawalan boleh ditingkatkan dengan memberi penekanan dalam aspek perubahan jisim pada subjek, pengatasan gangguan dan kestabilan. Oleh itu, skim kawalan yang komprehensif serta model dan trajektori yang lebih baik diperlukan untuk aplikasi ini. Dalam pemodelan, tambahan sendi dianggap mampu meningkatkan ketepatannya. Dalam perancangan trajektori, polinomial tingkat-keenam digunakan untuk memperbaiki trajektori yang dikehendaki. Sistem kawalan komprehensif telah direka dengan menekankan aspek keteguhan, pengatasan gangguan, dan kestabilan. Tiga pendekatan kawalan tidak tegak disiasat; Kawalan Mod Gelongsor (SMC), Kawalan Penegakan Suap-balik (FLC), dan Kawalan Jangkau Belakang (BSC). Keputusan menunjukkan ketepatan model kinematik dan model dinamik masing-masing meningkat sebanyak 24% dan 47%. Parameter perancangan trajektori adalah berterusan, dan tidak terdedah kepada sentakan atau lonjakan. Masa pelaksanaan ditambah baik sebanyak 11%, halaju terminal atas dan bawah masing-masing meningkat sebanyak 16.9% dan 20.9%. Tindak balas sistem tanpa gangguan menunjukkan hasil yang luar biasa dengan SMC, FLC, dan BSC. Ujian kekukuhan juga menunjukkan peningkatan luar biasa dalam parameter tersebut, kedua-duanya sebanyak 53% dan 126%. Keputusan ujian penolakan gangguan bersama keletihan, kekejangan, gegaran dan gabungan kesan gangguan menunjukkan penambahbaikan pada tindakbalas parameter-parameter. Oleh yang demikian, ia menunjukkan penambahbaikan walaupun terdapat perubahan kepada sistem. BSC menunjukkan

prestasi paling baik, diikuti dengan FLC dan SMC. Oleh itu, BSC disyorkan untuk sistem seperti ini.



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LIST OF SYMBOLS AND ABBREVIATIONS

A	-	For All
a_1	-	Length of the Shank Segment
a_2	-	Length of the Thigh Segment
a_3	-	Length of the Truck Segment
a_4	-	Length of the Neck Segment
α	-	Momentum coefficient
c	-	Gain of Controller
$Deg / ^\circ$	-	Angle in Degrees
e	-	Exponent
$f(x)$	-	Function f of x
f	-	Function f
$g(x)$	-	Function g of x
g	-	Function g
≥ 0	-	Greater than or equal to 0
l_1	-	Length of Centre of Mass for the Shank Segment
l_2	-	Length of Centre of Mass for the Thigh Segment
l_3	-	Length of Centre of Mass for the Truck Segment
l_4	-	Length of Centre of Mass for the Neck Segment
m	-	Metre
mA	-	Milli-Amphere
m_1	-	Mass of the Shank Segment
m_2	-	Mass of the Thigh Segment
m_3	-	Mass of the Truck Segment
m_4	-	Mass of the Neck Segment

θ_j	-	Bias for the j^{th} Angle
$u(t)/u$	-	Control Law
η	-	Sliding Mode Controller Parameter
GS	-	Global Stability
ANN	-	Artificial Neural Network
BD	-	Body Dynamics
BP	-	Back Propagation
BPGD	-	Back Propagation Gradient Descent
BSC	-	Backstepping Control/Controller
CNS	-	Central Nervous System
EL	-	Euler-Lagrange
ELM	-	Euler Lagrange Method
FES	-	Functional Electrical Stimulation
HT	-	Homogeneous Transformation
IRCSC	-	Integral of Rate of Change in Stimulation Current
IRCTSC	-	Integral of Rate of Change in Time Stimulation
ISC	-	Integral of Stimulation Current
ITE	-	Integral of Tracking Error
ITSC	-	Integral of Time Stimulation Current
ITTE	-	Integral of Time Tracking Error
LC	-	Lyapunov Criteria
LC	-	Lyapunov Criteria
LESC	-	Lyapunov Exponential Stability Criteria
LF	-	Linearized Feedback
LFC	-	Linearized Feedback Control/Controller
MCS	-	Maximum Control Signal
NE	-	Newton-Euler
NEM	-	Newton-Euler Method
NS	-	Nervous System
PID	-	Proportional Integral Derivative
PIDC	-	Proportional Integral Derivative Control/Controller
PP	-	Phase Plane

RBD	-	Rigid Body Dynamics
RMSE	-	Root Mean Square Error
SCI	-	Spinal Cord Injury
SM	-	Sliding Mode
SMC	-	Sliding Mode Control/Controller
STS	-	Sit-to-Stand



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

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CHAPTER 1

INTRODUCTION

1.1 Background information

The nervous system (NS) performs the coordination of the human body. The associated signals being electrical; the origin of which is ionic currents, this property made the utilisation of electrical signals crucial for so many medicinal purposes. Examples of which include: pain suppression wound healing and muscle conditioning [1-3]. In functional electrical stimulation (FES) usually, electrical signals of individual characteristics are used (generally of low amplitudes). It helps to revert or reduce abnormalities in utterances or responses of the human body parts due to ailments, injury or complications (examples are: spinal cord injury, head injury, stroke and other neurological disorders) which are usually controlled by the central nervous system (CNS) [4]. The function reversal/revival of the affected body part is achieved by systematically applying the desirable electrical signals to the appropriate muscles/nerves [5-7]. Figure 1.1 is a brief demonstration of how the functional electrical stimulation (FES) is accomplished. In reality, it is usually connected to the muscle group responsible for the target activity.

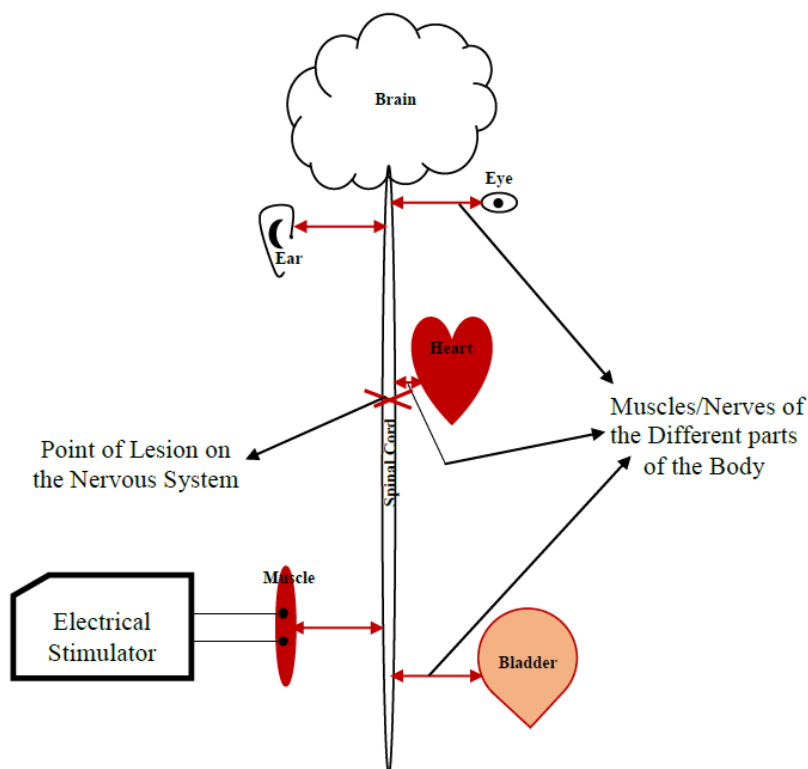


Figure 1.1: FES and the NS interaction

As demonstrated by Figure 1.1 FES has numerous applications some of which include: in the remedy of loss in urine control, in hearing restoration, in viewing disorders and in alleviating or solving problems of moving the parts of the body. The issue of urinary incontinence can be mitigated by applying the signals to the nerves responsible for bladder control which are found in the peritoneum. Hearing problems are also reduced with the aid of microphone as a transducer of the received audio signals to electrical signals after which they are converted to suitable signals that are used to stimulate the nerves inside the ear for audio. FES signals are also used to solve viewing problems with the aid of human-made retina. The cells responsible for viewing are stimulated with a proper signal after being processed from a camera. In human body joint movements, suitable FES signals are applied to the appropriate muscles via electrodes mounted on them. It could be internal or external which are technically known as implant or surface mount respectively [8].

1.2 FES induced movement

Restoration of different functions to some extent have been achieved with the aid of functional electrical stimulation (FES) in people with nervous system impairment due to spinal cord injuries (SCIs), brain injuries, strokes and related diseases. Reestablishment of skeletal movements to a certain degree such as abilities to grasp, cycle, reach and walk were some of the accomplishments of FES [9-12]. The nervous system manages and controls all protocols and actions executed by the body. It comprised up of the central and peripheral nervous systems. The first comprises of the brain and the spinal cord; the brain is the centre of management and control, and it connects to other body parts through the spinal cord, and the latter provides a platform for interconnections to the central nervous system [13]. The active cells of the nervous system used for movement coordination are the sensory and motor neurons. Records gave credit to the work of Liberson et al. in 1961 as the earliest practical application of FES as walking aid and the device produced was for foot drop disorder management. High level of success was attained in electro-neuroprosthesis applications from the 1980s due to the emergence of microprocessors which gave room for reduction in sizes and higher level devices multiplexing [14]. Walking is a movement activity that is facilitated in a regular repeated manner, and it has two primary components: the stance and swing. The stance action has to do with standing and related manoeuvres while the swing involves changes in joint(s) angles and utterances related to the angular rotation of joints [15-17].

FES is employed for therapeutic purpose in conditions where recovery is possible such as cerebral palsy and stroke; it is used mainly to train the nerves which eventually lead to their recovery [18-20]. It is also applied for movement restoration usually in cases where recovery is not possible as in the case of the majority of spinal cord injuries, achieved by initially training the nerves until eventually, they respond very well to the stimulation signals [21-29]. FES could be implemented individually, but usually, for active movement applications such as walking and rigorous exercise, it is employed with other assistive devices.

1.3 FES with emphasis on lower limb and SCI

FES is achieved by mimicking the operations of the nervous system due to its inability to send desired signals as results of the ailments. Suitable electrical signals are transmitted to the appropriate muscular nerves by the functional electrical stimulators via electrodes [30, 31], as described in Figure 1.2.

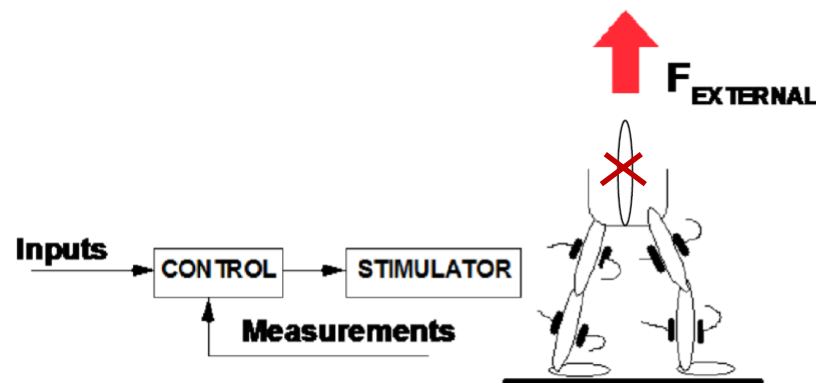


Figure 1.2: Movement restoration using FES

Figure 1.2 is an illustration of the process where the crossing is an arbitrary point indicating the area where discontinuity or the problem occurs on the central nervous system, and usual activities below the point are impaired. It is arbitrary in the sense that in some cases the problem might be in the brain itself. So, also the point of stimulation as earlier mentioned it has to be selected depending on the function restoration required.

SCI can be classified as complete or partial. In the case of complete SCIs, both sensory and motor functions are lost, while in partial SCIs one of the two is partially or wholly impaired. Figure 1.3 is an illustration of how the SCI is classified.

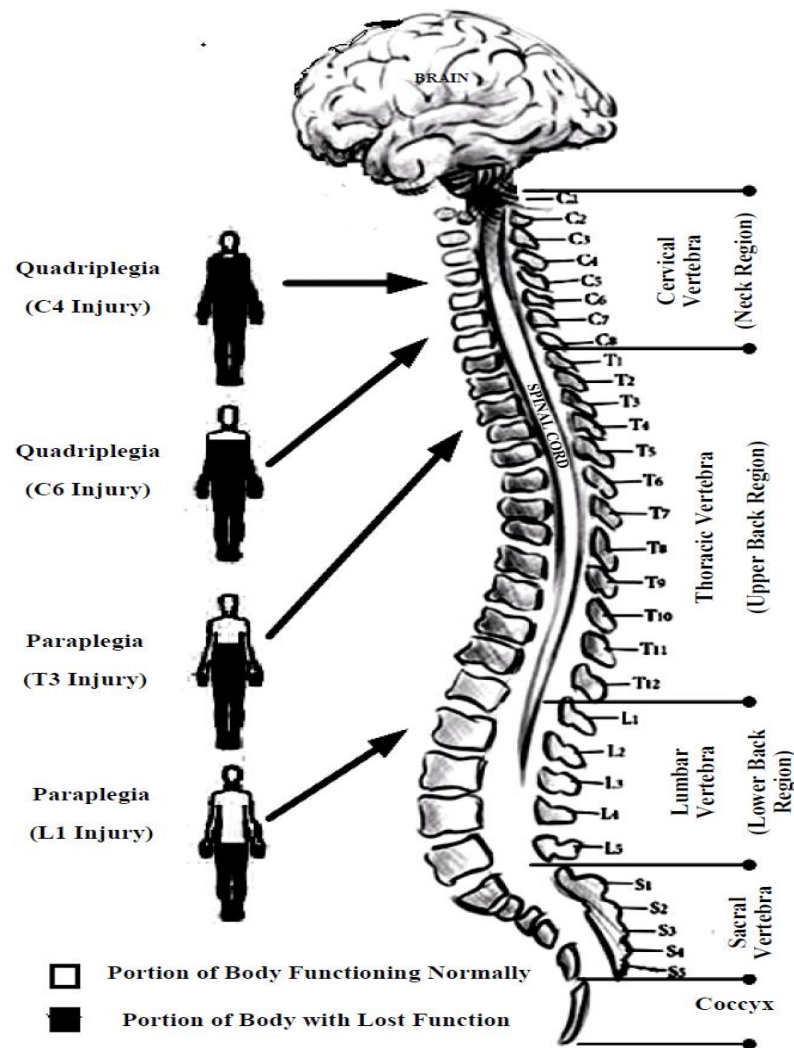


Figure 1.3: Classification of SCIs [32].

Another category is based on a portion of the lesion, and a brief explanation is as indicated in Figure 1.3. The vertebral column houses the spinal cord and gives it protection. The vertebral column consists of 31 bones, and it can be sub-classified into the cervical vertebra, thoracic vertebra, lumbar vertebra, the sacral vertebra bones and the coccyx accordingly. Quadriplegia results when the SCI occurs at the first bone of the thoracic vertebra or above, motion and sensing capability below the point of injury is lost; both the arms and legs cannot be moved intentionally. Paraplegia, on the other hand, occur when the damage occurs below the first bone in the thoracic vertebra. Also, sensation and motion below the point are hindered; both legs cannot be moved. Triplegia is a condition whereby sensory and motion in a single arm and both of the lower limbs are impaired. Hemiplegia occurs due to the impairment of movement and sensation in an arm and a leg in the same half of the body [32, 33].

1.4 The justification for the research

FES assisted sit-to-stand movement is achieved merely by providing support for the subject which will create more self-sufficiency (independence). Even though the majority of FES control systems for movement restoration in the lower limb are an open loop, but due to the requirement for performance which goes along with safety, the closed loop become the viable option [34, 35].

In the current world, records indicate high figures in occurrences of nervous system disorders. For instance, data showed that Denmark had between 10,000 to 15,000 new cases of stroke with a survival rate of one-fifth within the first month and a half within four years [36]. In North America, over a million individuals living with spinal cord ailments [37]. In the United States, there are about a quarter of a million SCI patients and about 12,000 of recent incidence occurrences. The record also eighty percent occur in the masculine gender with a mean age of forty years, with approximately forty-two percent from automobile accidents, twenty-seven percent from accidental fallings, fifteen percent from unrests and eight percent from sports activities [38]. The figures for new stroke cases is up to the tune of or more significant than 700,000 per year [39]. Ireland and the United Kingdom have an average of 45,000 spinal cord injury subjects with annual increments greater than 1,000. Highest figures of victims fall within 18 and 35 years age groups [40]. Reports by the World Health Organization (WHO) also indicate a global rise in neurological disorder cases as well as projections [41, 42].

Scanty amount of devices available for helping the patient group with a nervous disorder. For instance, according to the decision of the Centers for Medicare & Medicaid Services (CMS) (which is part of 'the Department of Health and Human Services (HHS), United States of America (USA)') on the use of FES devices for spinal cord injury subjects in order to improve functional abilities, only the Parastep-I system was approved [43]. And no new decision on the matter was issued up to date. It also states that just that device was approved by the US Food and Drug Administration (FDA) agency to aid in standing and to walk. The Parastep-I system was classified as a Class III system, and it has not gone through the Premarket Approval Application (PMA) process. Such category of FES devices (that is for standing and walking) is to undergo more severe checks on efficiency as well as safety compared to their counterparts.

Artificially stimulated muscles tend to fatigue faster than when naturally stimulated [44-51]. It contributes to time the dependent and nonlinear nature of the plant/system (neural-muscular-skeletal plant/system) [52, 53] and this presents a severe challenge in FES application. Of course, other additional complexities include the time delay from the nervous system, spasticity, tremors and others. An option for subsiding the effect of fatigue is the use of a closed-loop control system/control technique [54, 55] which is sufficiently adaptive and robust [56, 57]. Using feedback with predictive knowledge could also be beneficial for alleviating the problem of fatigue [58, 59]. Further suppression of other issues, e.g. spasticity, tremors are part of the current challenges. So also the question is re-tuning for each subject and of course the issue stability whose requirement is very stringent. Solving these persistent problems could lead to attaining clinical acceptance by more devices [54, 60-67].

Application of FES induced movements from all indication is promising. It is not only limited to restoration of movements alone but also for rehabilitation and therapeutic purposes. Existing systems are designed to operate open loop configurations. Efforts were made to shift to closed-loop systems for the FES in order to reap the benefits of automation but are yet to attain clinical approval. Linear control techniques were applied, but the results seem to be unsatisfactory which could be due to the nature of the plant and available sensors. Intelligent approaches were proposed, and results were hopeful in achieving clinical acceptability, but the absence of mathematical models in dealing with such techniques makes information/analysis on stability and robustness lacking, which may be produced using the nonlinear approach. Nonlinear control could suppress the issues regarding the plant as well, and the schemes have been proposed for the closed loop FES assisted movement systems, the results were encouraging. Therefore, these control strategies can be explored as the basis for controlling the neural-muscular-skeletal plant, with the strong expectations that could lead to obtaining/ascertaining the facts necessary which other techniques are deficient of or have failed to provide efficiently. For instance, the stability issue could be determined or improved from information on operational bandwidth or limits, and hence control scheme improvement. Knowledge of how to test for stability when the intelligent techniques are employed may also emerge. Therefore, it could lead to simplification of other things more especially integration with the intelligent approach which portrays proficiency and it's not limited to that, others are optimising power consumption as well as learning capability.

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APPENDIX A: Publications

The publications originated from the research work which yielded the thesis. It comprises conference of proceedings and journal papers.

Conference Papers

- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, (2017) Evolution of Intelligent And Nonlinear Control Approaches For Fes Induced Movement Generation of The Lower Limb, *Advances in Cooperative Robotics*: pp. 596-607.
- Mohammed Ahmed, M. S. Huq, B. S. K. K. Ibrahim, Aisha Ahmed, Zainab Ahmed, (2016) New Concepts for FES-Induced Movements, *IOP Conf. Series: Materials Science and Engineering* 160 (2016) 012104 doi:10.1088/1757-899X/160/1/012104.
- Ahmed, M., Huq, M. S., & Ibrahim, B. S. K. K. (2018). Restoration of Movement using FES: An Introductory Study I. In *IOP Conference Series: Materials Science and Engineering* (Vol. 341, No. 1, p. 012009). IOP Publishing.
- Ahmed, M., Huq, M. S., & Ibrahim, B. S. K. K. (2018).” Symposium on Electrical, Mechatronics and Applied Science 2018 (SEMA’18)” Manuscript Accepted.

Journal Papers

- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, (2017). SMC Scheme for FES Aided Restoration of STS Movement in Paraplegics. *International Journal of Integrated Engineering*, 9(4).
- Ahmed, M., Huq, M. S., & Ibrahim, B. S. K. K. (2017). Kinematic Modelling of FES Induced Sit-to-stand Movement in Paraplegia. *International Journal of Electrical and Computer Engineering (IJECE)*, 7(6), 3060-3069.
- Ahmed, M., Huq, M. S., Ibrahim, B. S. K., & Ahmed, A. (2018). A Preliminary Evaluation of Linear Control Schemes for FES-Assisted Movements. *Malaysian Journal of Movement, Health & Exercise*, 7(1).

- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "Sliding Mode Control of FES Aided Restored Movement," IEEE Transactions on Control Systems Technology, Manuscript Preparation in Process.
- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "Evaluation of Linearized Feedback Control Technique for Restoration of Sit-to-Stand Movement in Paraplegia," *IET Control Theory & Applications*, Manuscript Preparation in Process.
- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "FES Induced Restoration of STS Manoeuvre utilising the Backstepping Control Technique," *Automatica*, Manuscript Preparation in Process.
- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "Improved Trajectory Planning for FES-Induced STS Movement Restoration in Paraplegia," *Robotica*, Manuscript Preparation in Process.
- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "An Improved Dynamic Model for FES Assisted Sit-to-Stand Movement in Paraplegia," *International Journal of Integrated Engineering (IJIE)*, Manuscript Preparation in Process.
- Ahmed, M., M. S. Huq, B. S. K. K. Ibrahim, "Comparison of Nonlinear Control Techniques for the Regulation of Functional Electrical Stimulation Induced Sit-to-Stand in Paraplegia," IEEE Transactions on Control Systems Technology, Manuscript Preparation in Process.

